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# The late Holocene mollusc fauna of the Aral Sea and its biogeographical and ecological interpretation

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## Abstract

The Aral Sea, in 1960 the fourth largest lake on Earth, has since experienced a catastrophic environmental change, which appears to be mainly a result of human impact. Here, we attempt to add to a better understanding of environmental changes during the last millennium by using fossil mollusc assemblages obtained from 10 sediment cores, which were taken by gravity coring in 1991. The biogeographical analysis demonstrates that no endemic molluscs have existed in the Aral Sea during the last 1000 years. The investigated taxa are of Caspian and Palaearctic origin. The molluscan biodiversity is much lower than previously assumed and particularly low for such a large lake, indicating unstable ecological conditions during the period investigated. Using comparative ecological analyses of thanatocoenoses and stable isotope ratios in gastropod shells, we conclude that the main lake level changes of the last millennium were strong and abrupt, showing relative high stands at about 1300 AD and 1650 AD.
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***Keywords:*** Aral Sea; Holocene; Lake sediments; Molluscs; Stable isotopes; Lake level change

## Introduction

The Aral Sea is located in western Central Asia; its northern half is administered by Kazakhstan and the southern half by Uzbekistan. In 1960, it had a surface area of 66,500 km$^2$ and was the fourth largest lake on Earth. Its maximum depth was 68 m. Salinity was relatively low, averaging 5–10 g/l (Micklin 1991). A number of freshwater and brackish-water species co-existed (Zenkevich 1963). Since then the Aral Sea has shrunk in surface area to less than 25,000 km$^2$ (Bendhun and Renard 2004; Peneva et al. 2004). The northernmost part has been separated and is called the Small Aral Sea. The western part of the Large Aral Sea is almost separated nowadays. Thus, it is probable that in only a few years, the Aral Sea basin will be occupied by three distinct lakes. In 2003, its maximum depth was around 30 m and thus had decreased to less than half compared to 1961. Salinity increased correspondingly to about 90 g/l in the western lake basin (Zavialov et al. 2003; Friedrich and Oberhänsli 2004). Values differ extremely between places. For example, the Small Aral Sea into which the Syr Darya River flows is still brackish (Friedrich and Oberhänsli 2004). The species composition of Aral Sea habitats has changed extremely since the 1960s. Not taking into consideration *Caspiohydrobia* species overall about 44 species were registered in macrobenthic communities of the lake in the 1960s

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and 1970s (Andreeva 1989). By the end of the 20th century, the majority of aboriginal species had disappeared. Five species remained (three introduced and two native) and started to thrive in conditions of increased salinity (Filippov 1995a, 2001). Since then the situation has slightly improved in the Small Sea whereas in the Large Sea extremely high salinity caused almost complete extinction of all the species (Mirabdullayev et al. 2004).

It is generally accepted that the desiccation of the Aral Sea is largely man-made although the impact of naturally induced changes cannot yet be assessed. There is a lack of palaeolimnological proxy-studies which can be used to outline the environmental history of the Aral Sea in sufficient detail to forecast the future lake environment. Boomer et al. (2000) reviewed the palaeolimnology of the Aral Sea, based on analysis of Ostracoda, Foraminifera and Diatomacea from surface sediments and cored sediments some metres in length (Maev et al. 1983; Mayer 1983; Aleshinskaya 1991; Boomer et al. 1996).

Until recently, only a few radiocarbon dates had been published (Maev and Maeva 1991) which could be used for some kind of age correlation. During the last years, however, the stratigraphic knowledge about Holocene sediments and lake level changes increased significantly (e.g., see Boroffka et al. 2006; Austin et al. 2007; Sorrel et al. 2007a, b; Reinhardt et al. 2008) providing the opportunity to put own results in a more complex context.

Aral Sea molluscs have been reported commonly, but the number of species listed in the literature cannot be verified owing to the lack of proper documentation and statistical analysis. As biodiversity patterns play a major role in ecosystem analyses, our study more accurately documents the mollusc assemblages for the interpretation of environmental change in the Aral Sea during the last millennium.

The aim of the study is twofold. On the one hand, a better understanding of environmental changes in the Aral Sea during the last millennium shall be reached with the aid of studying biodiversity patterns through time, with focus on molluscs, and on the other hand, and vice versa, we try to add to the knowledge how certain environmental changes control biodiversity patterns. Particularly, we want to test whether the Aral Sea environment has favoured high species diversity in certain molluscan taxa, such as *Caspiohydrobia*, or a high diversity of ecophenotypes representing a few or a single species only.

## Materials and methods

Mollusc composition and abundance were studied in 10 short sediment cores (40–67 cm) taken in the northern and eastern parts of the Aral Sea by gravity coring using a helicopter in August and September 1991 (see Fig. 1). A detailed description of sampling methods has been published by Zhamoida et al. (1997). Four of the 10 cores that we used (numbers 48, 83, 103, 129) were sliced up immediately after they were retrieved; the length of sections was based on lithological differences. Six cores were left intact and were sliced up in October 2001. The preservation of these cores differed in that some were broken and others remained in one piece. The latter were cut into 4-cm-thick slices. Broken and badly preserved cores were cut into larger pieces in order to avoid mixing of material from different layers. Hence, the size of individual core sections varies substantially. The dried core length measured in 2001 was slightly different from the original length, measured during sampling. Thus, the original length of each section was calculated by multiplying the dried core length by the ratio of original core length/dried core length. These numbers are given in Table 1.

Each core section was treated with a 4% solution of $H_2O_2$ for 15–20 h and then washed and sieved using mesh sizes of 0.5, 0.25 and 0.125 mm. The sieved remains were numbered as follows: fraction 1 ($>0.5$ mm), 2 ($<0.5$ mm $>0.25$ mm) and 3 ($<0.25$ mm $>0.125$ mm). The mollusc shells were picked out, mounted on stubs, sputtered with gold and examined with the aid of a Cambridge scanning electron microscope (SEM). In the case of *Caspiohydrobia* of which 23 Aral Sea species have been described in the literature, 250 shells were examined under the SEM, while other taxa were investigated only in numbers of up to 50 specimens.

Shell parameters and indexes measured and used in gastropods and bivalves are shown in Table 2 and in Figs. 2 and 3.

The deviation of the distribution of shell parameters for *Caspiohydrobia* from a Gaussian distribution was tested using the Kolmogorov–Smirnov test (Sokal and Rohlf 1998). For age-dependent characteristics and indexes, the corresponding regression lines versus number of whorls were calculated and then residuals were tested for normality using the same test. All calculations were performed using GraphPad Prism 3.0 software.

To reveal the main patterns of species succession and to identify different periods in the Aral Sea history, a cluster analysis was undertaken on the basis of data on benthic invertebrate composition and abundance in individual core sections. Since the core sections contained a lot of damaged and partly preserved shells as well as significant amount of shell debris, it was difficult to give exact numbers of shells per section. For this reason, the species abundance was given in grades of occurrence: 1, rare (1 or 2 specimens per section); 2, low (3–9); 3, common (10–50); 4, abundant ($>50$–100); 5, highly abundant ($>100$).

Data from cores which were badly preserved and those collected near the shore were excluded, because of

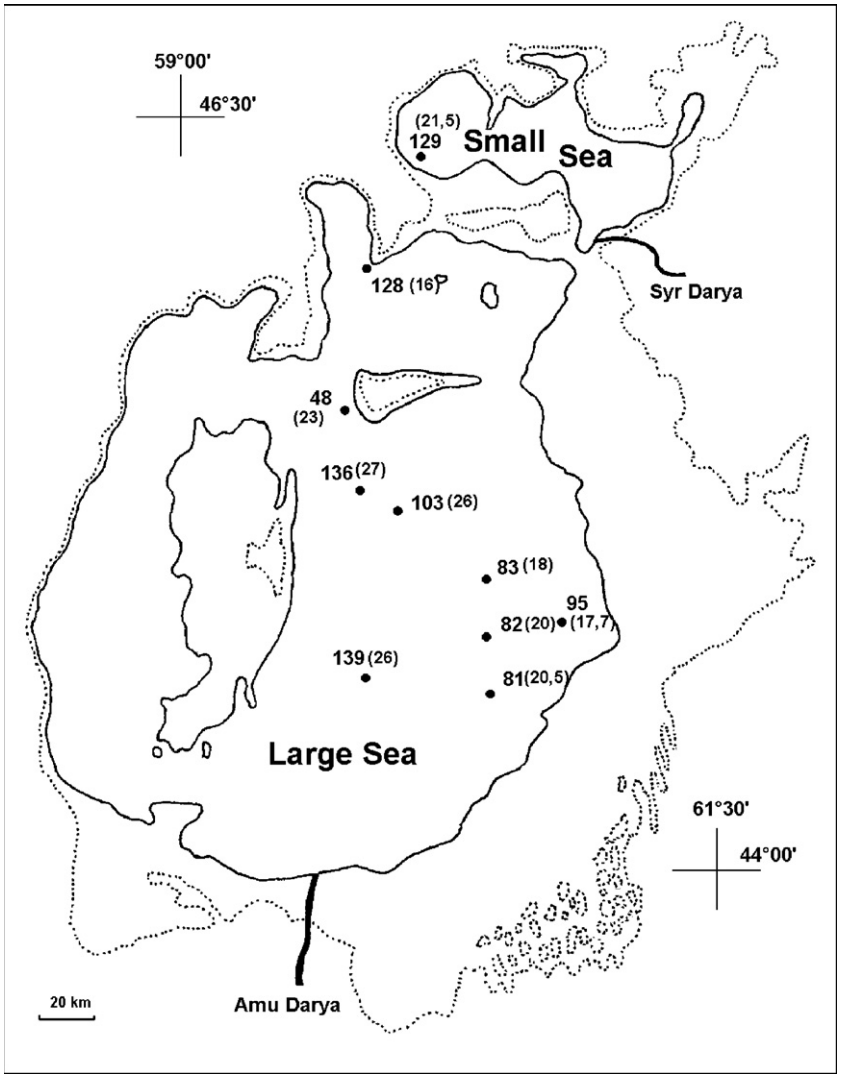


**Fig. 1.** Location of coring sites at the Aral Sea. Identification numbers from Zhamoida et al. (1997); in brackets water depths of 1960 in metres. Dotted line represents the shore in 1960, the solid line the shore in 1991, the year of coring.

**Table 1.** Total lengths of cores, identification numbers and base of cut sections (in cm)

| Section | Core number | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 48 | 81 | 82 | 83 | 95 | 103 | 128 | 129 | 136 | 139 |
| 1 | 1.5 | 4.2 | 4.3 | 1.5 | 3.8 | 5.0 | 13.3 | 5.0 | 5.4 | 5.2 |
| 2 | 3.5 | 8.4 | 8.5 | 3.0 | 7.5 | 10.0 | 26.7 | 10.0 | 10.8 | 10.4 |
| 3 | 7.0 | 12.5 | 12.8 | 3.6 | 11.3 | 16.0 | 40.0 | 16.0 | 16.2 | 15.1 |
| 4 | 10.0 | 16.7 | 17.1 | 7.5 | 15.0 | 20.0 | | 22.0 | 21.6 | 19.7 |
| 5 | 14.0 | 20.9 | 21.4 | 13.5 | 30.1 | 24.0 | | 30.0 | 27.0 | 24.3 |
| 6 | 20.0 | 25.1 | 25.6 | 19.5 | 47.0 | 30.0 | | 38.0 | 32.4 | 28.9 |
| 7 | 30.0 | 29.3 | 29.9 | 24.5 | | 35.0 | | 46.0 | 37.8 | 33.6 |
| 8 | 40.0 | 33.5 | 34.2 | 28.5 | | 36.0 | | 52.0 | 43.2 | 39.4 |
| 9 | 51.0 | 37.6 | 38.5 | 37.0 | | 39.0 | | 59.0 | 48.6 | 44.0 |
| 10 | 63.0 | 41.8 | 42.7 | 38.0 | | 44.0 | | | 54.0 | |
| 11 | 67.0 | 46.0 | 47.0 | 41.0 | | 49.0 | | | | |
| 12 | | | | 45.0 | | | | | | |

Identification numbers as in Zhamoida et al. (1997).

**Table 2.** Shell parameters and indexes measured and used in gastropods and bivalves

| | |
|---|---|
| DN | Diameter of *n* (1–6) whorl |
| DP | Diameter of protoconch |
| H | Maximum height of shell |
| HA | Height of aperture in direction of shell axis |
| HL | Height of last whorl |
| H/L | Relative height of shell |
| HL/H | Relative height of last whorl |
| L | Maximum length of shell (in bivalves) |
| LA | Maximum length of aperture |
| LA/H | Relative height of aperture |
| N | Total number of whorls |
| NP | Number of protoconch whorls |
| P1 | Length of prodissoconch 1 |
| P2 | Length of prodissoconch 2 |
| W | Maximum width of shell |
| WA1 | Width of aperture perpendicular to shell length axis |
| WA2 | Width of aperture in relation to LA |
| WA2/LA | Relative width of aperture |
| W/H | Relative width of shell |
| W/L | Relative width of shell (in bivalves) |
| WNS | Maximum width of non-spiral part (of protoconch) |

the high possibility of including allochthonous material which had been washed out from the nearby coastal cliffs or transported to the coring sites by turbidites. Thus, only cores 81, 82, 83, 103, 136 and 139 from the Large Aral Sea were used for the cluster analysis. Percent similarity was calculated as a measure of similarity between separate sections:

$$PSc_{ij} = 200\frac{\sum_{k=1}^{n}\min(x_{ik}, x_{jk})}{\sum_{k=1}^{n}(x_{ik} + x_{jk})}.$$

where $PSc_{ij}$ is the measure of similarity between sections $i$ and $j$; $x_{ik}$ and $x_{jk}$ is the abundance of species $k$ in section $i$ and in section $j$, correspondingly.

The weighted average method was applied for the clustering procedure (Jongman et al. 1999). As a result, the most parsimonious dendrogram was obtained, and individual clusters were identified. For each cluster, the mean values of species abundance were calculated. The cluster analysis was performed using MVSP 3.12 (Kovach Computing Services) software.

AMS-$^{14}$C-dating was conducted at the Leibniz Laboratory of the Christian-Albrechts-Universität Kiel www.uni-kiel.de/leibniz using fruits of the water plant *Ruppia* which were obtained from core 82, sections 8 and 9.

Analyses of $\delta^{13}$C and $\delta^{18}$O of shells of *Caspiohydrobia* were conducted by Michael Joachimski, Institute of Geology and Mineralogy of Erlangen University. Carbonate powders were reacted with 100% phosphoric acid (density > 1.9, Wachter and Hayes 1985) at 75 °C in an online carbonate preparation line (Carbo-Kiel-single sample acid bath) connected to a Finnigan Mat 252 masspectrometer. All values are reported in per mil relative to V-PDB by assigning a $\delta^{13}$C value of + 1.95 and a $\delta^{18}$O value of −2.20 to NBS19. Reproducibility was checked by replicate analysis of laboratory standards.

## Results and discussions

### Taxonomical identification

Shells of four gastropod and six bivalve species were found in the cores:

Gastropoda *Caspiohydrobia grimmi* (Clessin et Dybowski, 1888), Hydrobiidae, Caenogastropoda
*Turricaspia* cf. *spica* (Eichwald, 1855), Pyrgulidae, Caenogastropoda
*Theodoxus pallasi* (Lindholm, 1924), Neritidae, Neritimorpha
*Valvata macrostoma* (Moerch, 1864), Valvatidae, Heterobranchia

Bivalvia *Abra ovata* (Philippi, 1836) Semelidae, Heterodonta
*Dreissena caspia* (Eichwald, 1855), Dreissenidae, Heterodonta
*Dreissena polymorpha* (Pallas, 1771), Dreissenidae, Heterodonta
*Cerastoderma isthmicum* (Issel, 1869), Cardiidae, Heterodonta
*Cerastoderma rhomboides* (Lamarck, 1819), Cardiidae, Heterodonta
*Hypania minima* (Ostroumoff, 1907), Lymnocardiidae, Heterodonta

### Taxonomical remarks

***Caspiohydrobia* (Figs. 4a–d)**

Until 1970, this gastropod from the Aral Sea was usually identified as representing the Mediterranean species *Hydrobia ventrosa* Mont and/or the Caspian endemic species *Hydrobia grimmi*. On the basis of external shell morphology and biogeographical considerations, Starobogatov (1970) coined the new genus *Caspiohydrobia* for the presumed endemic species and changed the name of *H. grimmi* to *Caspiohydrobia conica* (synonym: *Pyrgohydrobia conica*; Logvinenko and Starobogatov (1968)). *Caspiohydrobia* was then attributed to the rissooidean family Pyrgulidae. In 1974, Starobogatov described the new species *Caspiohydrobia husainovae*. Between 1981 and 1989, 21 more *Caspiohydrobia*-species from the Aral Sea were differentiated mainly with the aid of certain shell parameters

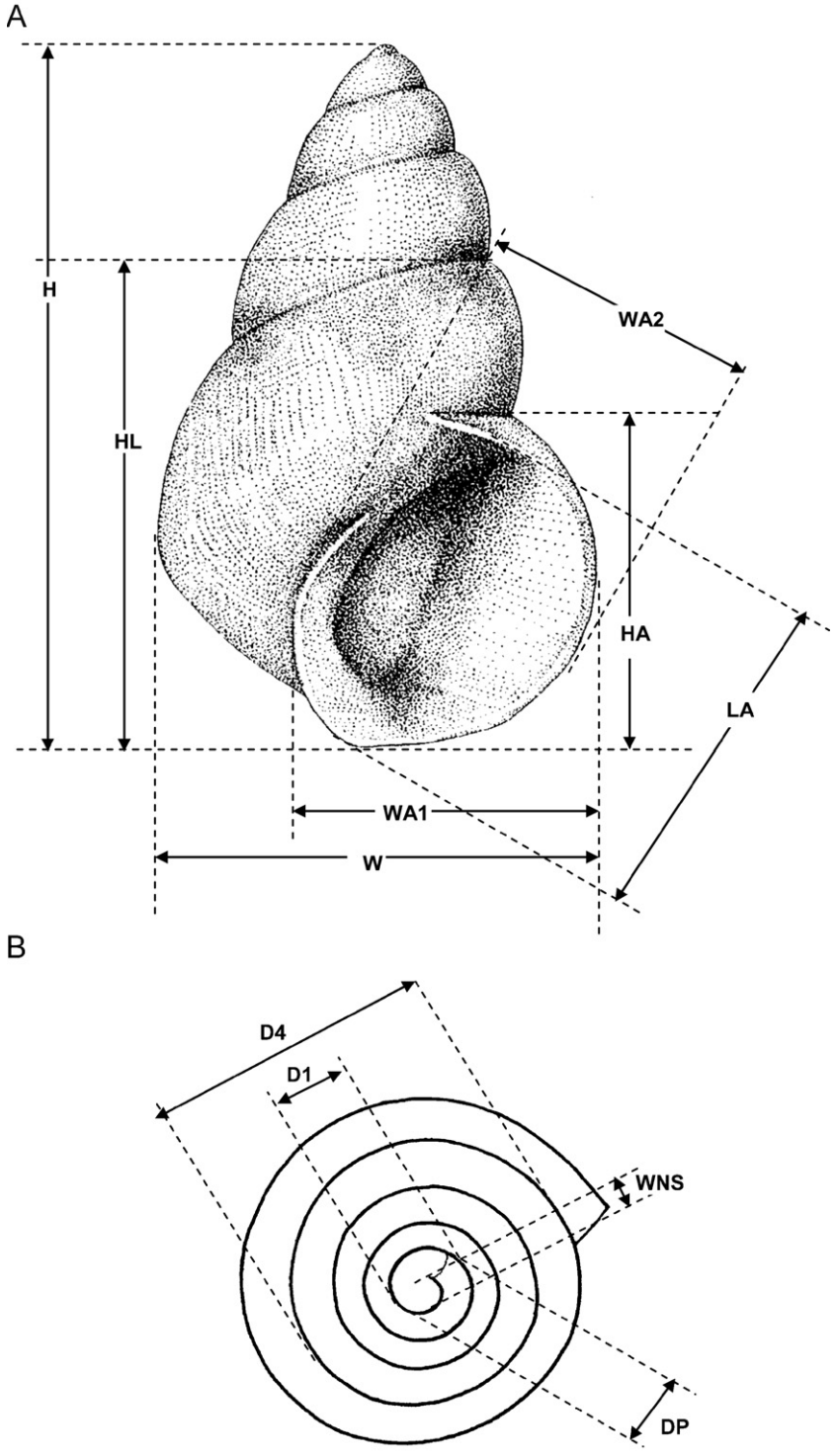


**Fig. 2.** Measured parameters in gastropod shells: (A) apertural view and (B) apical view. Further explanation in text. Not to scale.

(Starobogatov and Andreeva 1981; Andreeva 1987; Izzatullaev 1987). Anatomical investigations by Sitnikova et al. (1992) suggested that *Caspiohydrobia* species are systematically closer to Hydrobiidae than to Pyrgulidae. Furthermore, the examination of the reproductive systems of four ''species'' exhibited no clear interspecific differences (Sitnikova et al. 1992).

In order to get a clearer picture of the diversity of the Aral Sea *Caspiohydrobia*, we evaluated additional shell characters, particularly those of the early ontogenetic shells and made a statistical analysis using the parameters indicated in ''Materials and methods'' section (Fig. 5). There are no significant shell morphological differences, which can be used to differentiate species. In

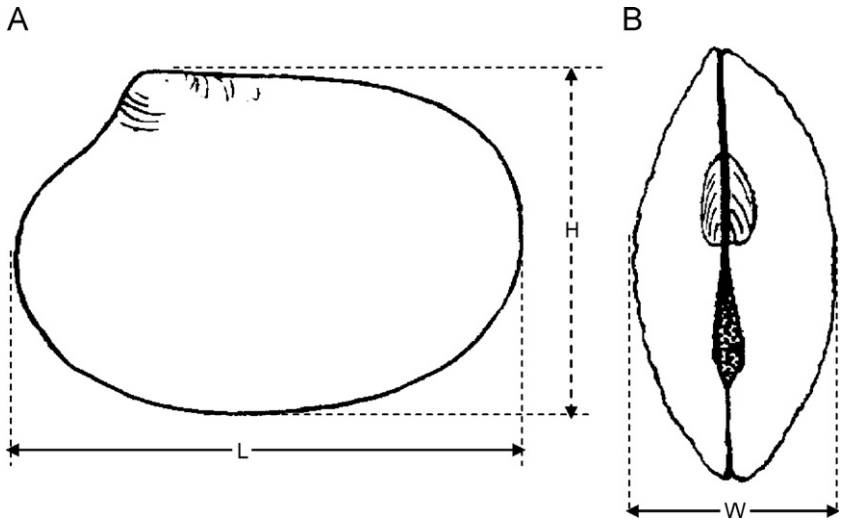


**Fig. 3.** Measured parameters in bivalve shells: (A) lateral view and (B) apical view. Further explanations in text. Not to scale.

these analyses, ontogenetic changes in shell shape were included (see Fig. 5). The Kolmogorov–Smirnov test showed that the distribution of all measured parameters of *Caspiohydrobia* shells does not deviate from a Gaussian distribution.

Measurements on the protoconchs confirm the relative homogeneity of shell shape. All the specimens analysed under the SEM exhibited a uniform protoconch sculpture (Fig. 4b). The protoconch parameters are summarised in Table 3.

### *Turricaspia* (Figs. 4e and f)

*Turricaspia* cf. *spica* has originally been described from the Caspian Sea (Eichwald 1838). According to Starobogatov (1974), the shells of this species were only infrequently found in Aral Sea sediments. The same species identification was provided in later descriptions (e.g., Maev et al. 1983). To our knowledge, no other species of *Turricaspia* was ever reported from the Aral Sea.

In the description of the Caspian Sea specimens, Logvinenko and Starobogatov (1968) gave the following measurements: maximum of nine whorls, maximum height of 10 mm and maximum width of 3.1 mm. The largest specimen found in our short cores has 8.8 whorls, 5.3 mm high and 1.8 mm wide. Our material does not show any potential interspecific differences. Protoconchs of all examined specimens have a smooth surface without any distinctive sculpture. The protoconch parameters are summarised in Table 4.

### *Theodoxus* (Figs. 4g–i)

Starobogatov (1974) reported two *Theodoxus* species from the Aral Sea, *T. pallasi* and *T. zhukovi* Kolesnikov. While *T. pallasi* was found alive in the Aral Sea, from *T. zhukovi* only shells from Quaternary sediments of the southern shore of the Aral Sea are known. In the cores under consideration, only *T. pallasi* was found.

According to Starobogatov (1974), in the Aral Sea *T. pallasi* has a maximum height of 5.5 mm and a maximum width of 7.5 mm. The largest specimen found in our short cores was 2.6 mm high and 4.9 mm wide in shell size. Most of the shells were heavily corroded. Thus, the examination of the protoconch was possible only in a very few specimens. In such relatively well-preserved protoconchs, no distinctive sculpture could be detected except for growth increments (Fig. 4i). The protoconch type indicates the embryonic feeding of nurse eggs which is also known from other *Theodoxus* species (Riedel 1993). The protoconch parameters are summarised in Table 5.

### *Valvata* (Figs. 4j and k)

Valvatids have not yet been described from the Aral Sea proper. The shells found in the cores are relatively small and represent remains of juvenile *V. macrostoma*. According to Zhadin (1952: *V. pulchella*), the shells of *V. macrostoma* having four whorls may reach a height of 2 mm and a width of 4 mm. Glöer (2002) noted about 3–4 whorled shells having a height of 2–3 mm and a width of 3.5–5 mm. The largest specimen found in our short cores has 2.2 whorls, 0.72 mm high and 1.2 mm wide. The protoconchs exhibit the typical valvatid sculpture (see Riedel 1993) having numerous spiral lirae which are radially interconnected (Fig. 4k). The protoconch parameters are summarised in Table 6.

### *Abra* (Figs. 4l and m)

From published data, in the Aral Sea the shells of *A. ovata* have a maximum length of 25 mm, a H/L ratio ranging from 0.62 to 0.82, and a W/L ratio ranging from

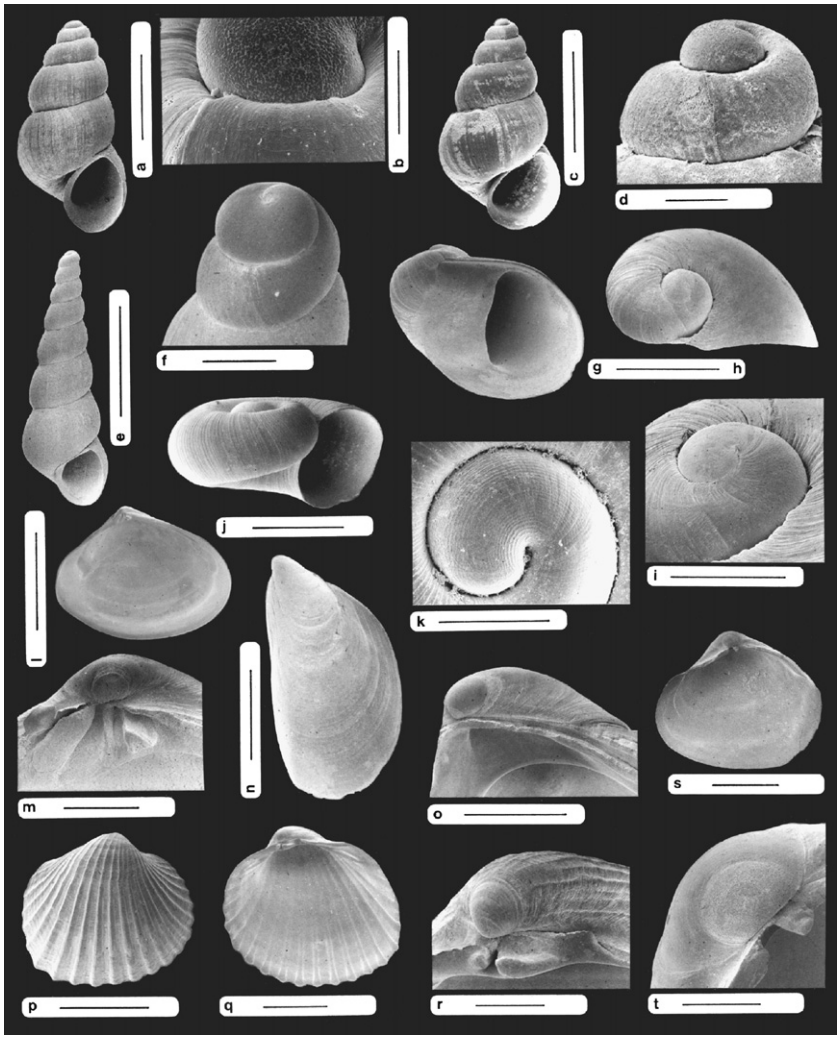


**Fig. 4.** Shells of Aral Sea molluscs. All figured specimens are juveniles. (a) Teleoconch of *Caspiohydrobia grimmi* from sediment surface sample. Scale line = 1 mm. (b) Same specimen as in (a), magnification of the apex showing the transition from protoconch to teleoconch and the microsculpture of the protoconch. Scale line = 0.05 mm. (c) Teleoconch of *Caspiohydrobia grimmi* from core 81/5; other morphotype than in (a). Scale line = 1 mm. (d) Same specimen as in (c), magnification of the apex. Scale line = 0.1 mm. (e) Teleconch of *Turricaspia* cf. *spica* from core 139/8. Scale line = 2 mm. (f) Same specimen as in (e), magnification of the apex exhibiting a two-whorled protoconch. Scale line = 0.2 mm. (g, h) Teleoconch of *Theodoxus pallasi* from core 139/8, in apertural and apical view. Scale line = 1 mm. (i) Same specimen as in (g) and (h), close-up of the apex exhibiting the typical protoconch of *Theodoxus* spp. Scale line = 0.4 mm. (j) Teleoconch of *Valvata macrostoma* from core 95/6, in apertural view. Scale line = 0.5 mm. (k) Same specimen as in (j), close-up of apex showing the typical microsculpture of valvatids. Scale line = 0.2 mm. (l) Valve of *Abra ovata* from core 139/1, internal view. Scale line = 2 mm. (m) Same specimen than in (l), close-up of hinge and prodissoconch. Scale line = 0.2 mm. (n) Valve of *Dreissena polymorpha* or *D. caspia* from core 139/8, external view. Scale line = 2 mm. (o) Other specimen as in (n) from core 139/8, magnification of hinge and prodissoconch. Scale line = 0.5 mm. (p) Valve of *Cerastoderma isthmicum* or *C. rhomboides* from core 82/3, external view. Scale line = 1 mm. (q) Valve of *Cerastoderma isthmicum* or *C. rhomboides* from core 82/3, internal view. Scale line = 1 mm. (r) Same specimen as in (q), magnification of hinge and prodissoconch. Scale line = 0.2 mm. (s) Valve of *Hypania minima* from core 81/3, internal view. Scale line = 0.5 mm. (t) Same specimen as in (s), magnification of hinge and prodissoconch. Scale line = 0.1 mm.

0.38 to 0.5 (cf. Starobogatov 1974). In our short cores, the largest specimen has a maximum length of 13.7 mm, an H/L ratio of 0.77 and a W/L ratio of 0.40. In respect of prodissoconch parameters, Karpevich (1964) gave numbers for specimens from the Sea of Azov. According to this, prodissoconch 1 has an average length of 0.1 mm and prodissoconch 2 measures >0.14–0.15 mm. *A. ovata* recovered from our cores exhibits an average length of prodissoconch 1 of about 0.11 mm and of prodissoconch 2 of about 0.17 mm (in both cases $n = 23$). Prodissoconch 2 shows distinct growth increments (Fig. 4m).

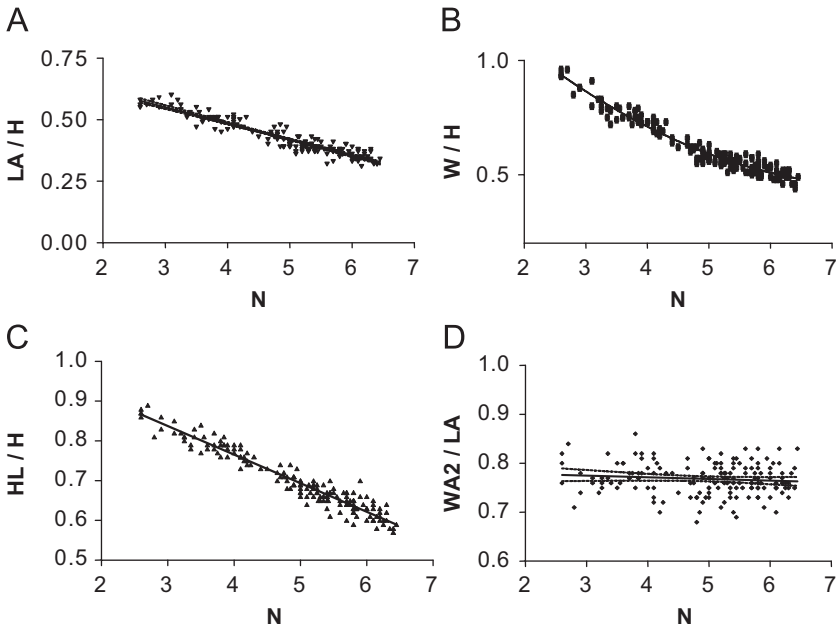


**Fig. 5.** Regression analysis of certain shell parameters of *Caspiohydrobia grimmi* from Aral Sea short cores: (A) relative height of aperture, (B) relative width of shell, (C) relative height of last whorl, (D) relative width of aperture. Dots are measured values, lines are calculated regressions. Horizontal axis is number of whorls, vertical axis is value of the shell parameter. See text for further explanations.

**Table 3.** Protoconch measurements in *Caspiohydrobia grimmi*

| *Caspiohydrobia grimmi* protoconch parameters | Mean | Minimum | Maximum | *n* |
|---|---|---|---|---|
| Diameter in microns | 284 | 223 | 348 | 165 |
| Number of whorls | 1.5 | 1.3 | 1.7 | 126 |
| Maximum width of non-spiral part in microns | 44 | 16 | 85 | 151 |

**Table 4.** Protoconch measurements in *Turricaspia* cf. *spica*

| *Turricaspia* cf. *spica* protoconch parameters | Mean | Minimum | Maximum | *n* |
|---|---|---|---|---|
| Diameter in microns | 379 | 342 | 449 | 21 |
| Number of whorls | 2.1 | 1.9 | 2.4 | 22 |
| Maximum width of non-spiral part in microns | 58 | 21 | 107 | 22 |

**Table 5.** Protoconch measurements in *Theodoxus pallasi*

| *Theodoxus pallasi* protoconch parameters | Mean | Minimun | Maximum | *n* |
|---|---|---|---|---|
| Diameter in microns | 527 | 505 | 550 | 2 |
| Number of whorls | 1.1 | 1.1 | 1.1 | 2 |
| Maximum width of non-spiral part in microns | 120 | 50 | 147 | 7 |

**Table 6.** Protoconch measurements in *Valvata macrostoma*

| *Valvata macrostoma* protoconch parameters | Mean | Minimum | Maximum | *n* |
|---|---|---|---|---|
| Diameter in microns | 393 | 352 | 435 | 2 |
| Number of whorls | 1.1 | 1.0 | 1.1 | 2 |
| Maximum width of non-spiral part in microns | 59 | 44 | 75 | 2 |

***Dreissena* (Figs. 4n and o)**

Two species of the zebra-mussel have been described from the Aral Sea, *D. caspia* and *D. polymorpha* (see Starobogatov 1974) the assumed interspecific differences of which are not well documented, however. Soft parts have not been examined in detail and molecular data are non-existent. The shell morphological data have not been tested statistically. In *D. polymorpha*, a keel is pronounced and in *D. caspia* it is not. We are unable to decide whether two species exist in the Aral Sea (Zhadin 1952; Starobogatov 1974). Since there was no strict statistical criterion, it was impossible to decide confidently whether the keel was pronounced or not. From our cores, we obtained juvenile shells the features of which accord with both species.

Starobogatov (1974) gave measurements for Aral Sea specimens of both "species". According to this, the maximum length of *D. caspia* is 17 mm, the H/L ratio ranged from 0.38 to 0.68 and the W/L ratio varied from 0.3 to 0.56. Measurements for *D. polymorpha*: 25 mm length, H/L ratio of 0.39–0.50, W/L ratio of 0.38–0.50.

In our short cores, the largest specimen has a length of 14.8 mm, H/L ratio of 0.40 and a W/L of 0.36. Karpevich (1964) provided data on the early ontogenetic shell of *Dreissena* sp. from the Aral Sea: prodissoconch 1 of 0.055–0.065 mm and prodissoconch 2 of about 0.2 mm average length. In *Dreissena* sp. from our short cores, the prodissoconch 1 has an average length of 0.09 mm ($n = 7$) and prodissoconch 2 of about 0.25 mm ($n = 6$) (Fig. 4o).

***Cerastoderma* (Fig. 4p–r)**

The Aral Sea cockles were initially assigned to *Cardium edule* Linné (e.g., see Zhadin 1952). However, this species represents the type species of *Cerastoderma* Poli, 1795. Starobogatov (1974) reported two species living in the Aral Sea, *Cerastoderma lamarcki* (Reeve) and *C. umbonatum* (Wood). Later on Kafanov (1980) referred to the same species as *C. rhomboides* and *C. isthmicum*, respectively. It was reported that until the 1960s, *C. rhomboides* occupied much of the Aral Sea proper while *C. isthmicum* inhabited mostly shallow bays and adjacent sea areas with increased salinity. After 1980, *C. rhomboides* was assumed to be extinct while *C. isthmicum* spread throughout the Sea (Andreeva 1989).

In respect of our short cores, these two species were distinguishable when more or less adult specimens were recovered. In juveniles, it was usually not possible to differentiate species. According to Starobogatov (1974), the maximum shell length of *C. rhomboides* in the Aral Sea is 55 mm and 30 mm in *C. isthmicum*. The largest specimen obtained from the cores has a length of 23 mm, H/L ratio of 0.91 and a W/L ratio of 0.8. Karpevich (1964) gave measurements for the early ontogenetic shells of *Cerastoderma* sp.: prodissoconch 1 with average length of 0.1 mm and prodissoconch 2 within a length range of 0.2–0.23 mm. Our data coincide with these measurements (Fig. 4r): prodissoconch 1 with an average length of 0.11 mm ($n = 8$) and prodissoconch 2 with an average length of 0.21 mm ($n = 9$).

***Hypania* (Figs. 4s and t)**

This name is also in use for a genus of the Polychaeta, coined by Ostroumoff (1897). However, the name had been introduced much earlier ("Pander" Kupffer, 1831) (cited in Millard 2001) for the bivalve studied here. Thus, a new name for the polychaet has to be found.

In the latest systematic revision by Starobogatov (1974), two species of *Hypania* living in the Aral Sea were recognised: *H. vitrea* (Eichwald) and *H. minima* (Ostroumoff). Three endemic subspecies were considered (Starobogatov 1974). *H. minima* were widely spread throughout the Aral Sea in the first half of the 20th century while *H. vitrea* was known by single findings from the Amu Darya delta. In our short cores, we found only shells of *H. minima*.

According to Starobogatov (1974), in the Aral Sea, the shells of *H. minima* have a maximum length of 20 mm, an H/L ratio ranging from 0.68 to 0.77 and a W/L ratio of 0.4–0.5. In the cores, the largest specimen had a maximum length of 10 mm, an H/L ratio of 0.7 and a W/L ratio of 0.44. Karpevich (1964) wrote that prodissoconch 1 in this species is measuring 0.08–0.11 mm, not providing data on prodissoconch 2. Our measurements: average length of prodissoconch 1 is 0.12 mm ($n = 12$) and that of prodissoconch 2 is 0.25 mm ($n = 14$) (Fig. 4t).

## Ecology

***Caspiohydrobia***

In the early 20th century, Hydrobiidae s.l. were reported to be relatively rare animals in the Aral Sea (Behning 1935). In the 1960s, these molluscs were observed throughout the Sea in relatively high numbers, reaching a biomass of 4 g/m$^2$ (Andreeva 1989). In the 1990s, *Caspiohydrobia* was the most abundant macrobenthic animal, although its biomass was much lower than that of other benthic macro-invertebrates (Filippov 1997). By the end of the 1990s, these molluscs were still observed in the Large Aral Sea while the salinity had reached 60 ppt here (Zholdasova, personal communication). *Caspiohydrobia* is considered to be halophilic and usually should benefit from a salinity increase. According to some experimental studies (Filippov and Komendantov 1996), this gastropod is able to tolerate salinities as high as 80 ppt. Field investigations (Andreeva 1989) showed that *Caspiohydrobia* does not have any preference in respect of depth and shows little substrate specificity. Some data (Filippov 1997) indicate that the

spatial distribution is closely connected with the distribution of aquatic plants.

***Turricaspia***

*Turricaspia* cf. *spica* has never been found alive in the Aral Sea. Starobogatov (1974) reported that *Turricaspia* shells occurred in hydrobiological samples occasionally but in his opinion, they were washed out from Quaternary or Upper Pliocene sediments. In contrast, Sidorov (1929) mentioned that shells of this species were usually well preserved and hence the species has probably become extinct in the recent past.

*T. spica*, living in the Caspian Sea, was registered in a depth range of 0–30 m in the western and northern parts of the central Caspian (Logvinenko and Starobogatov 1968) and thus inhabit brackish environments. Other ecological traits are not known.

***Theodoxus***

*T. pallasi* was one of the common components of the Aral Sea benthos in the first half of the 20th century. Beginning with the very first investigations, it was invariably reported from bio- and thanatocoenoses (Behning 1935; Yablonskaja 1960; Maev et al. 1983). In the late 1960s, its abundance decreased, which was considered the result of shrinking of areas occupied by aquatic plants and sandy sediments (Andreeva 1989). By the end of the 1970s, however, its abundance was partly restored although the area of its distribution was still much smaller than in the 1950s. In the 1990s, this species disappeared completely from the Aral Sea (Filippov 1995a, 1997).

The distribution of *T. pallasi* has been correlated with that of aquatic plants and hard substrates (Andreeva 1989). In the lower Volga delta/northern Caspian Sea, however, this species lives also on sandy to silty substrates (personal observation Riedel 2000). According to Starobogatov (1974), *T. pallasi* usually occupied the inshore zone of the Aral Sea down to a depth of 5–10 m. The relatively long persistence of this species in the shrinking Aral Sea may suggest a high salinity tolerance. Experimental investigations, however, have shown that in the Aral Sea a salinity of only up to 20 ppt is favourable for this species (see Filippov 1995b for a review). This does not coincide with the low salinity of 2 ppt where *T. pallasi* lives abundantly in the lower Volga delta/northern Caspian Sea (personal observation Riedel 2000). In *Theodoxus fluviatilis* from the Baltic Sea, however, a distribution could be observed within a salinity range of 1–16 ppt (Riedel unpublished). Thus, the distribution of *T. pallasi* in the Caspian Sea may have causes other than salinity (cf. Logvinenko and Starobogatov 1968 who labelled *T. pallasi* a species common in all parts of the Caspian Sea). According to Newman (1961, cited by Dillon 2000), *Theodoxus* spp. show no dietary specificity although some studies have shown that the guts contained 65% diatoms, 30% detritus and 5% algal filaments by volume (Jacoby, 1985, cited by Dillon 2000). This diet correlates well with the former distribution of *T. pallasi* in the Aral Sea.

***Valvata***

*V. macrostoma* has never been found alive in the Aral Sea. Sidorov (1929) reported that Valvatidae were completely absent in the Aral Sea and even in adjacent water-bodies. Elsewhere in Eurasia, *V. macrostoma* lives in the shore zones of lakes with low mineral content but occurs in temporary pools, swamps and meadows along rivers as well. It can tolerate a salinity of up to 2 ppt and can resist temporary drying-out (Zhadin 1952; Gittenberger et al. 1998; Glöer 2002; personal observation Riedel 2000).

***Abra***

*A. ovata* was introduced to the Aral Sea in the early 1960s in order to increase the food stock for commercial fish. In 1967 (Kortunova 1970), a population was recognised in the Bay of Sarychegahak (the place of introduction). In the late 1960s and early 1970s, *A. ovata* spread rapidly throughout the Aral Sea. By 1976, its expansion was basically completed. *A. ovata* became one of the main zoobenthos components, forming about 2/3 of the total zoobenthos biomass (Andreeva 1978). In the 1990s, this species was still holding the leading position in benthic assemblages, dominating in terms of biomass in all investigated areas (Filippov 1995a, 1997).

*A. ovata* occurs elsewhere in the marine Black Sea and the brackish Sea of Azov (Starobogatov 1974, personal observation Riedel 2003) and in 1939, it was also introduced to the Caspian Sea. In the Aral Sea, *A. ovata* burrows deeply into different types of soft substrata and is able to cope with strongly diluted seawater as well as with high salinity conditions (Filippov and Komendantov 1996). This species can tolerate low oxygen content. Its main food source is planktonic detritus but this bivalve is also able to collect fine detritus from the sediment surface with the aid of its siphon (Karpevich 1964).

***Dreissena***

The zebra mussels were the most common and most abundant mollusc species in the Aral Sea until the 1960s. In the 1950s and early 1960s, *Dreissena* prevailed in terms of biomass in benthic assemblages, occupying all sediment types in all water depths. In the late 1960s, the areas occupied by *Dreissena* were reduced considerably (Andreeva 1989). In the mid-1970s, its abundance was to some extent restored, but its average biomass then again decreased drastically and the species practically disappeared from the lake only a few years later (Andreeva 1989).

The former spatial distribution of *Dreissena* in the Aral Sea shows that these molluscs were extremely

eurybiotic and had no clear specificity in respect of depth and type of substrate, although in other lakes and rivers, a hard substrate is clearly preferred (personal observations Riedel). Experimental investigations of its salinity tolerance as well as data on its spatial distribution in the lake (see Filippov 1995b for a review) have shown that a salinity of up to 15–20 ppt is quite favourable. When the average salinity of the Aral Sea had reached 17 ppt, the bivalves had practically disappeared from benthic assemblages (Andreeva 1989).

### *Cerastoderma*

Numerous shells of *Cerastoderma* have been found on the Aral Sea shore and in the sediments of Aral Sea coastal terraces by scientists since the beginning of the 19th century (Khusainova 1961). Palaeontological investigations by Maev et al. (1983) suggest that *Cerastoderma* appeared in the Aral Sea region about 5 ky ago. In the first half of the 20th century, the cockles were relatively scarce in the Aral Sea proper but abundant in bays with increased salinity. In the late 1960s, a considerable reduction of the area occupied by *Cerastoderma* was observed; the average biomass, however, showed gradual growth. In the early 1970s, a sharp increase of *Cerastoderma* abundance occurred. Until recently, it was the second most abundant genus in the Aral Sea benthic assemblages in terms of biomass (Filippov 1997).

From the distributional patterns of *Cerastoderma* spp. in the Aral Sea, it is evident that these molluscs are extremely eurybiotic, capable of surviving in conditions of substantial fluctuation in respect of the lake level, salinity and other environmental factors. Experimental studies have shown that Aral Sea cockles are able to survive salinity as high as 60 ppt (Filippov and Komendantov 1996). *Cerastoderma* spp. burrow to shallow depth in soft substrata and live by filter feeding; they are capable of using fine detritus from the bottom via re-suspending surface sediments by powerful currents from the siphon and then filtrating the water (Filippov and Riedel personal observations).

According to Starobogatov (1974), in the Caspian Sea and the Aral Sea, *C. lamarcki* ( = *C. rhomboides*) lives in shallows with somewhat lowered salinity. This species occurs in the Mediterranean and in the Black Sea predominantly in brackish water habitats. *C. umbonatum* ( = *C. isthmicum*) occupies areas down to 30 m depth in the Caspian Sea. It also occurs in the Black Sea and in the Mediterranean including the hypersaline lakes of the North African coast (Starobogatov 1974).

### *Hypania*

*Hypania* spp. are considered to represent common components of the aboriginal Aral Sea fauna. The first data in respect of the Aral Sea refer to shells from coastal terraces (Basiner, 1848, cited in Khusainova 1961). In the 1950s, *H. minima*, *Dreissena* spp. and chironomids dominated the benthic assemblages. In the 1960s, the abundance started to decrease and by 1980 *Hypania* had disappeared from the Aral Sea (Andreeva 1989).

*Hypania* spp. burrow to shallow depths in sediments and live by filter feeding. In the Aral Sea, *Hypania* spp. showed no bathymetric preference occupying available habitats except for those with possible oxygen deficiency (Andreeva 1989). Experimental studies showed that they are able to tolerate a salinity increase up to 14–17 ppt (see Filippov 1995b for a review). A salinity of 17 ppt had been reached when *Hypania* disappeared from the Aral Sea during the late 1970s.

## Taxa distribution in the cores

### *Caspiohydrobia*

Shells occurred in relatively large amounts in all examined cores and in most of the core sections. They were distributed irregularly from base to top, but exhibited higher abundances in the lower part as well as in the upper part of the cores. This was expressed most clearly in the cores obtained from the open Large Aral Sea (cores 81–83, 103, 136, 139), while areas closer to the shore showed different patterns of *Caspiohydrobia* vertical distribution. Shells were rather evenly distributed in core 95. In the cores 48 and 129, the shells were obtained in substantial amounts only in the upper halves while the lower halves were almost devoid of shells.

### *Turricaspia*

Shells were observed in relatively large numbers (more than 100 specimens overall) in the lowest parts of cores 136 and 139 with the highest abundance at the base. Specimens were also found in the lowermost part of core 95. Although most of the shells were broken, some dozens were well preserved. As the sites of cores 136 and 137 are located in the central Large Aral Sea, the hypothesis that the shells of *T.* cf. *spica* represent reworked fossil material from outcrops (see Starobogatov 1974) cannot be supported. In that case, all shells of *T.* cf. *spica*, which are comparatively fragile, would have been destroyed during the long horizontal transportation process. Thus, *Turricaspia* cf. *spica* actually lived in the Aral Sea in the Holocene. The species was predominantly associated with *Caspiohydrobia*, *Cerastoderma* and *Dreissena*.

### *Theodoxus*

Shells were scarce in cores and there was no obvious trend in vertical distribution. A cluster analysis demonstrates that it occurred more often in core sections containing large amounts of *Dreissena*, *Caspiohydrobia* and chironomids.

### *Valvata*

Shells of *V. macrostoma* ($n = 5$) were found exclusively in the lowest section of core 95. This core was collected in the area close to the ancient delta of the Syr Darya (see Fig. 1). Broken shells of *Turricaspia* as well as some shells of *Hypania* and *Abra* were also found in the same core section. As *A. ovata* had been introduced to the Aral Sea only a few decades ago, it must be assumed that at least some part of the sediments of core 95 is allochthonous, probably in the form of river delta turbidites.

### *Abra*

*A. ovata* was found in the upper parts of all studied cores. In the cores 103, 136 and 139, it was confined to the uppermost sections, while it was observed also in more basal sections of the cores 81 (section 3), 82 (section 4) and 129 (section 3). This can be explained by the behaviour of *A. ovata* of burrowing as deep as 5–6 cm into the sediments (Filippov and Riedel personal observations).

### *Dreissena*

*Dreissena* spp. was second in abundance. Specimens were found in almost all core sections analysed. The highest abundance occurred in the lowest parts of cores 82 and 139. A higher than average abundance occurred also in the upper parts of cores 81, 136 and 139. Generally, the abundance fluctuated significantly with depth in the cores.

### *Cerastoderma*

*Cerastoderma* spp. shells were found in all cores but partly exhibited different distribution patterns. In most cores, a bimodal vertical distribution with maximum abundance in both upper and lower horizons could be recognised. There was no upper maximum in core 136 and no lower maximum in core 48. The overall vertical distribution of *Cerastoderma* spp. was similar to that of *Caspiohydrobia grimmi*. It is noteworthy that the maximum abundance of *Cerastoderma* spp. in the upper core sections was regularly one section higher than that of *Hypania*. This pattern corresponds well with the observed patterns of abundance dynamics of these species in the Aral Sea in the 1960s–1980s (Filippov 1997).

*C. rhomboides* mainly occurred in the lowest core sections while in the upper core sections *C. isthmicum* prevailed. Meanwhile many transitional forms were also available.

### *Hypania*

Shells of *H. minima* were found in all cores examined but were mainly in the upper parts. The deepest *Hypania* shells occurred in cores 81–83 while minimum distribution depth was registered in the cores 136 and 139, the sites of which are located more centrally in the Large Aral Sea.

## Dating

Fruits of the water plant *Ruppia* from two subsequent sections of core 82 were dated. The indicated identification numbers can be used to obtain the complete technical information from the responsible laboratory (see "Materials and methods" section). The results are shown in Table 7.

These two dates indicate that the upper 35 cm of core 82 cover the last 700 years of the lake history. Thus, the complete core roughly covers the last millennium. Despite the potentially different sedimentation regimes at the sites of the other cores, these dates can be used in

**Table 7.** Dating results from core 82

| | |
|---|---|
| *Ruppia*-fruits taken from 34 cm depth of core 82 | |
| Identification number of laboratory: KIA18247 Aral AF AMS 82-8-1 | |
| Radiocarbon age | BP 685∗33 |
| Calibrated age | cal AD 1295 |
| One sigma range | cal AD 1281–1303 (probability 45.1%) |
| Probability 68.3% | 1368–1383 (probability 23.2%) |
| Two sigma range | cal AD 1275–1325 (probability 57.2%) |
| Probability 95.4% | 1348–1391 (probability 38.2%) |
| *Ruppia*-fruits taken from 35 cm depth of core 82 | |
| Identification number of laboratory: KIA18248 Aral AF AMS 82-9-1 | |
| Radiocarbon age | BP 705 ± 38 |
| Calibrated age | cal AD 1288 |
| One sigma range | cal AD 1272–1302 (probability 56.0%) |
| Probability 68.3% | 1370–1381 (probability 12.3%) |
| Two sigma range | cal AD 1247–1254 (probability 1.0%) |
| Probability 95.4% | 1255–1323 (probability 70.6%) |
| | 1350–1390 (probability 23.9%) |

the context of a rough stratigraphic correlation calculated with the aid of the comparative analysis of organismic assemblages in the short cores (see "Comparative description of thanatocoenoses" section).

## Comparative description of thanatocoenoses

Sets of core sections similar in terms of mollusc communities and abundance were identified using a cluster analysis. Along with mollusc taxa, the data on chironomid and plant abundance were included in the analysis.

The most parsimonious dendrogram obtained in the course of the analysis (Fig. 6) was dissected at the arbitrary level of 65%. This particular level was chosen with the only purpose of obtaining a reasonable number of separate clusters, which would not also differ much in respect of their size (i.e., number of core sections included). In this way, the core sections were identified, which are similar in terms of mollusc taxa composition and abundance.

Overall, six types, A–F, of benthic assemblages could be differentiated (Figs. 6 and 7). Types A–D were observed throughout all investigated cores except for core 136 in which the assemblage of type A is missing (Fig. 7).

In the dated core 82, about 5 cm of sediments represent 100 years in average. Thus, the assemblages can be roughly correlated with age, considering, however, that sedimentation process varied significantly. Assemblage A existed from 1820 to 1991 AD (year of coring), assemblage B from 1475 to 1820 AD, assemblage C from 1390 to 1475 AD, assemblage D from 1305 to 1390 AD, assemblage E is not developed, assemblage F from 1135 to 1305 AD and again assemblage C from 1050 to 1135 AD. Subsequently, the assemblage types can tentatively be used to correlate sections of different cores. In the case of core 136, in which assemblage A is missing, it must be concluded that the core was not complete and 5–10 cm of the top sediments were lost during coring or subsequently.

Assemblage A is characterised by the exclusive occurrence of *A. ovata* which was introduced to the Aral Sea four decades ago and due to its burrowing behaviour, the shells of this species are found in sediments which date back to about 1820 AD.

Assemblage B is characterised by the occurrence of some *Theodoxus*, the highest and second highest abundances, respectively, of *Caspiohydrobia* and the three bivalve genera *Hypania*, *Cerastoderma* and *Dreissena* as well as chironomids.

In assemblage C, abundances are generally lower which is particularly significant in respect of *Hypania* and *Cerastoderma* (minimum amount). Interestingly, the sediments from these sections contained a significant amount of Trichoptera remains. *Theodoxus* is not part of this thanatocoenosis.

Assemblage D is characterised by the lack of *Hypania*, the highest abundance of *Cerastoderma* and the occurrence of very few *Theodoxus*. *Caspiohydrobia* is comparatively common. In core 103, this assemblage is significantly better pronounced as is reflected by the broader distribution within the sediment column.

Assemblage E is developed only in the cores 136 and 139 and is characterised particularly by the presence of *Turricaspia*. *Hypania* is not represented but *Theodoxus* is. The abundances of *Caspiohydrobia* and *Dreissena* are comparatively high. Cores 136 and 139 are the sites with the greatest water depths.

Assemblage F is developed in the cores 81–83. It is particularly characterised by low biodiversity and low abundances. *Caspiohydrobia* represents the most abundant taxon; however, its abundance is minimal compared to the other assemblages (Table 8).

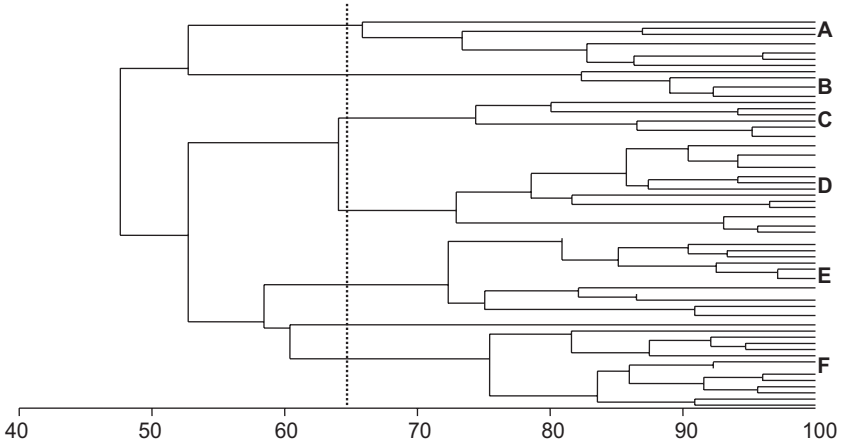


**Fig. 6.** Dendrogram of core section similarity. Dotted line represents a chosen level of tree section, A–F: the differentiated assemblages. The horizontal axis shows percent similarity.

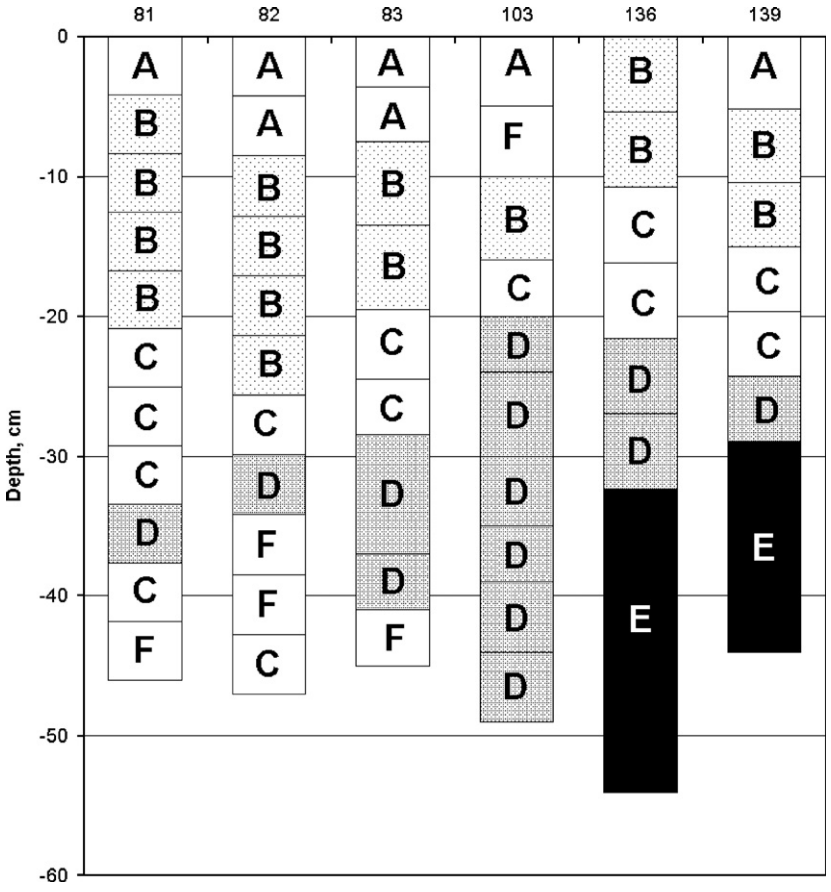


**Fig. 7.** Distribution of differentiated mollusc assemblages in the Aral Sea cores 81–83, 103, 136 and 139. The vertical axis shows sediment depth in centimetre.

**Table 8.** Average abundance of the main macro-components of fossil assemblages in the Aral Sea short cores in grades (see explanations in text)

| Assemblage | *Caspiohydrobia* | *Turricaspia* | *Theodoxus* | *Abra* | *Hypania* | *Cerastoderma* | *Dreissena* | Chironomidae | Plants |
|---|---|---|---|---|---|---|---|---|---|
| A | 2.6 | 0.0 | 0.0 | 2.9 | 1.3 | 2.4 | 1.5 | 0.0 | 0.1 |
| B | 4.1 | 0.0 | 0.7 | 1.4 | 3.5 | 2.9 | 3.7 | 0.4 | 0.0 |
| C | 3.0 | 0.0 | 0.0 | 0.0 | 0.9 | 0.7 | 3.1 | 0.2 | 0.0 |
| D | 3.7 | 0.0 | 0.1 | 0.0 | 0.0 | 3.6 | 1.3 | 0.1 | 0.9 |
| E | 3.9 | 2.6 | 0.8 | 0.0 | 0.0 | 2.6 | 3.3 | 0.3 | 0.6 |
| F | 2.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.8 | 0.4 | 0.0 | 0.0 |

## Stable isotopes

Shells of *Caspiohydrobia* from the cores 136 and 139 were analysed (Table 9) because the corresponding coring sites are located relatively centrally in deep water in the Large Aral Sea (see Fig. 1) and thus the sediments are probably undisturbed. Core 136 was taken from the northern central part while core 139 originates from the southern central part. The distance between the drilling localities is about 70 km (compare Fig. 1). The stable isotope data in relation to sediment depth are shown in Fig. 8. The age correlation of cores is based upon core section similarities. Ages are estimated using the correlation with core 82 which has been dated (see Table 7). Consequently, the core sections analysed may cover 900–1000 years. During this millennium, the $\delta^{13}C$ and $\delta^{18}O$ values of both cores show the same general trends, with $\delta^{13}C$ and $\delta^{18}O$ maxima at around 1150 AD and around 1500 AD, and minima between 1250 AD and 1400 AD and around 1650 AD. The amplitude in core 136 is generally stronger than in core 139 in respect of $\delta^{13}C$ as well as $\delta^{18}O$ values. The highest amplitude

**Table 9.** Stable isotope analyses $\delta^{13}C$ and $\delta^{18}O$ from *Caspiohydrobia grimmi* shells from the Aral Sea cores 136 and 139

| Core/section | Versus V-PDB | | | | Versus V-SMOW |
|---|---|---|---|---|---|
| | 13/12-C | S.D. | 18/16-O | S.D. | 18/16-O |
| 136/1 | 1.44 | 0.02 | −1.14 | 0.03 | 29.73 |
| 136/2 | 1.37 | 0.01 | −1.75 | 0.01 | 29.11 |
| 136/3 | 1.84 | 0.02 | −0.49 | 0.03 | 30.40 |
| 136/4 | 1.40 | 0.01 | −1.46 | 0.04 | 29.40 |
| 136/5 | 0.48 | 0.01 | −3.35 | 0.02 | 27.45 |
| 136/6 | −0.16 | 0.02 | −2.99 | 0.02 | 27.82 |
| 136/7 | 1.86 | 0.02 | −1.40 | 0.02 | 29.46 |
| 136/8 | 0.72 | 0.02 | −2.08 | 0.04 | 28.77 |
| 136/9 | 1.48 | 0.01 | −1.24 | 0.04 | 29.63 |
| 136/10 | 1.78 | 0.02 | −1.38 | 0.02 | 29.49 |
| 139/1 | 1.23 | 0.02 | −0.24 | 0.03 | 30.66 |
| 139/2 | 1.28 | 0.02 | −1.04 | 0.02 | 29.83 |
| 139/3 | 1.40 | 0.00 | −1.76 | 0.04 | 29.10 |
| 139/4 | 2.00 | 0.01 | −1.35 | 0.02 | 29.52 |
| 139/5 | 1.90 | 0.03 | −1.59 | 0.03 | 29.27 |
| 139/6 | 1.32 | 0.01 | −2.08 | 0.02 | 28.76 |
| 139/7 | 1.70 | 0.01 | −2.22 | 0.03 | 28.62 |
| 139/8 | 1.75 | 0.02 | −2.03 | 0.02 | 28.81 |
| 139/9 | 1.27 | 0.02 | −2.03 | 0.04 | 28.81 |

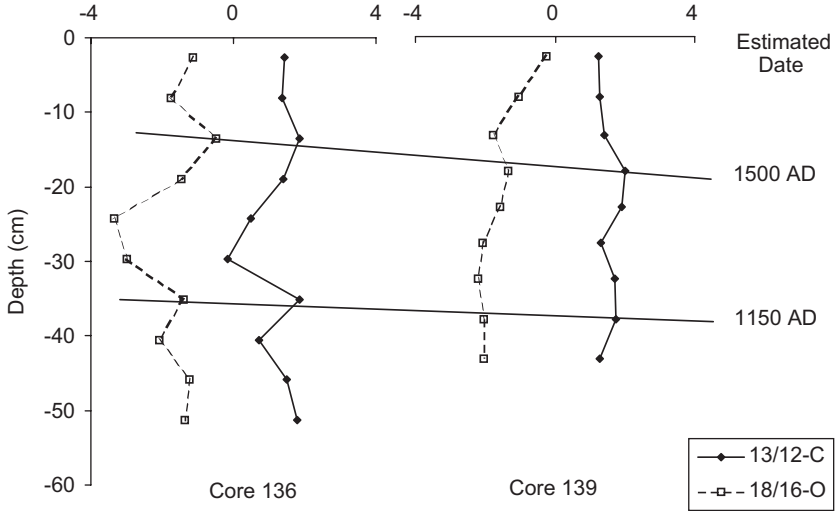


**Fig. 8.** Stable isotope data obtained from *Caspiohydrobia* plotted against depth in cores 136 and 139 with date estimates indicated.

(lowest values) of $\delta^{13}C$ and $\delta^{18}O$ values refers to the period 1250–1400 AD (see "Discussion" section).

## Discussion

The sediment cores examined cover a period of about 1000 years, going back from 1991, the year in which they were obtained. The record of mollusc shells in the cores is continuous. The taxa which could be identified can be assigned to the Ponto-Caspian faunal province with the exception of *V. macrostoma* which is part of the Palaearctic province. In respect of *A. ovata*, *C. isthmicum* and *C. rhomboides*, however, it must be emphasised that the biogeography is not clear due to systematic and taxonomic problems.

It was shown that no endemic mollusc species have existed in the Aral Sea during the last millennium. In all but one case (*V. macrostoma*), it must be concluded that the mollusc species have been introduced from the Caspian Sea. The essential question whether 23 species of *Caspiohydrobia* have inhabited the Aral Sea

(Starobogatov and Andreeva 1981; Andreeva 1989) was answered. Although it cannot be excluded that cryptic species in the *Caspiohydrobia*-complex exist, only one morpho-species was found and this result is of importance for the interpretation of the Aral Sea in general. As there is no example in the phylogeny of gastropods that endemic radiations and evolution of species flocks, respectively, have happened in short-lived, environmentally unstable lakes, it must be concluded that the evolution of such a species flock in *Caspiohydrobia* in the Aral Sea would have required a relatively stable ecosystem for at least several thousands of years. That the environment was not stable has been documented in different respects (see e.g., Boomer et al. 2000; Austin et al. 2007). The great intraspecific variability in *Caspiohydrobia grimmi* suggests unstable environmental conditions particularly with regard to salinity and temperature changes. Comparable shell-morphological reactions have been demonstrated in other ecosystems and habitats, respectively (see e.g., Bandel et al. 1997; Bandel and Riedel 1998; Riedel et al. 2001).

The environmental change in the Aral Sea during the last millennium is directly mirrored by the sequence of five to six different faunal assemblages found in the cores. The clear synchronisation of separate species abundance fluctuations demonstrates that these patterns were not accidental oscillations but reflect real large-scale changes in the ecosystem.

Some particular events shall be discussed. The brackish water species *Turricaspia* cf. *spica* occurred only in the lowermost parts of the cores 136 and 139 and probably became extinct in the Aral Sea about 1300–1350 AD. The phase between 1250 and 1400 AD is characterised by the lowest values of $\delta^{13}C$ and $\delta^{18}O$, which may indicate increased freshwater inflow and thus decreasing salinity. It can be speculated that *Turricaspia* cf. *spica* could not adapt to the probably near-freshwater conditions. A stronger water supply during this period is related by Boomer et al. (2000) to the Amu Darya, which started again to contribute to the Aral Sea after humans had lost control over the artificial diversion of the river to the south (Sarykamysh depression). This was probably true, but our data indicate that the Syr Darya in the northeast had an even stronger influence. This may be concluded from the higher amplitude of peaks in stable isotope ratios in the more northern location of core 136 compared to the location of core 139 which is closer to the Amu Darya delta in the south. Thus, it can be supposed that the precipitation was generally higher and particularly in the catchment area of the Syr Darya in the Tianshan. The sediments of Lake Issyk-Kul in the Tianshan for instance, probably could be used to verify our assumption; however, the studies which have been carried out in this respect outline the Holocene lake evolution excluding the last millennium (e.g., see Ricketts et al. 2001).

Subsequent to the regional extinction of *Turricaspia* cf. *spica*, assemblage D developed with increased abundances of *Caspiohydrobia* and *Cerastoderma* which prefer brackish to saline water and a strongly decreased abundance of *Dreissena* which prefers freshwater. This change happened about 1350–1400 AD and a further increasing salinity until 1500–1550 AD can be assumed due to the stable isotope ratios which show maxima at about 1500 AD. These maxima can most likely be interpreted as mirroring less inflow of freshwater and higher evaporation, respectively. The next significant change is reflected by the introduction of *H. minima* which, according to Izzatullaev and Starobogatov (1991), had reached the Aral Sea in the Aspheronian (1.6–0.7 my BP). Our data suggest that *H. minima* was newly introduced after the low lake level at 1500 AD, possibly by man. Single finds of *H. minima* in assemblage F indicate that it existed in the Aral Sea until about 1300 AD and thus became temporarily extinct in the same period as *Turricaspia* cf. *spica*. Another lake level high stand is indicated by minima of stable isotope ratios around 1650 AD. This may be supported by the lack of remains of aquatic plants at the coring sites (“deep” water) and the increased abundance of *Dreissena*.

The period of appearance of the freshwater species *V. macrostoma* in the lowermost part of core 95 cannot be estimated; however, due to the well-preserved shells, we conclude that they have been transported very little or not at all and are more or less autochthonous. It is likely that the species had lived in a river delta (possibly the ancient Syr Darya), which could progress far into the basin of the Large Aral Sea, and thus indicates a low lake level and probably high salinity. Freshwater molluscs have also been reported from cores taken nearby by Maev et al. (1983). Alternatively, *V. macrostoma* could indicate that the Aral Sea was a freshwater lake during that time. However, there are no data from central basin sediments supporting this idea. There is no evidence of a lake level high enough to trigger an outflow which would be the precondition to establish a freshwater Aral Sea.

Late Holocene lake level changes of the Aral Sea were discussed, e.g., by Boroffka et al. (2006); Austin et al. (2007); Sorrel et al. (2007b) and Reinhardt et al. (2008).

Generally, it can be concluded that the environmental changes were partly as strong and rapid as the modern fall in lake level since the early 1960s (Fig. 9). The Aral Sea ecosystem was more unstable during the last millennium than has been recently presumed (for a review, see Boomer et al. 2000). Since the Neolithic period humans have influenced the water budget of the Aral Sea (e.g., see Boroffka et al. 2006), this influence has certainly increased quite strongly during the last millennium and particularly in the 20th century. However, the differentiation of man-made and natural

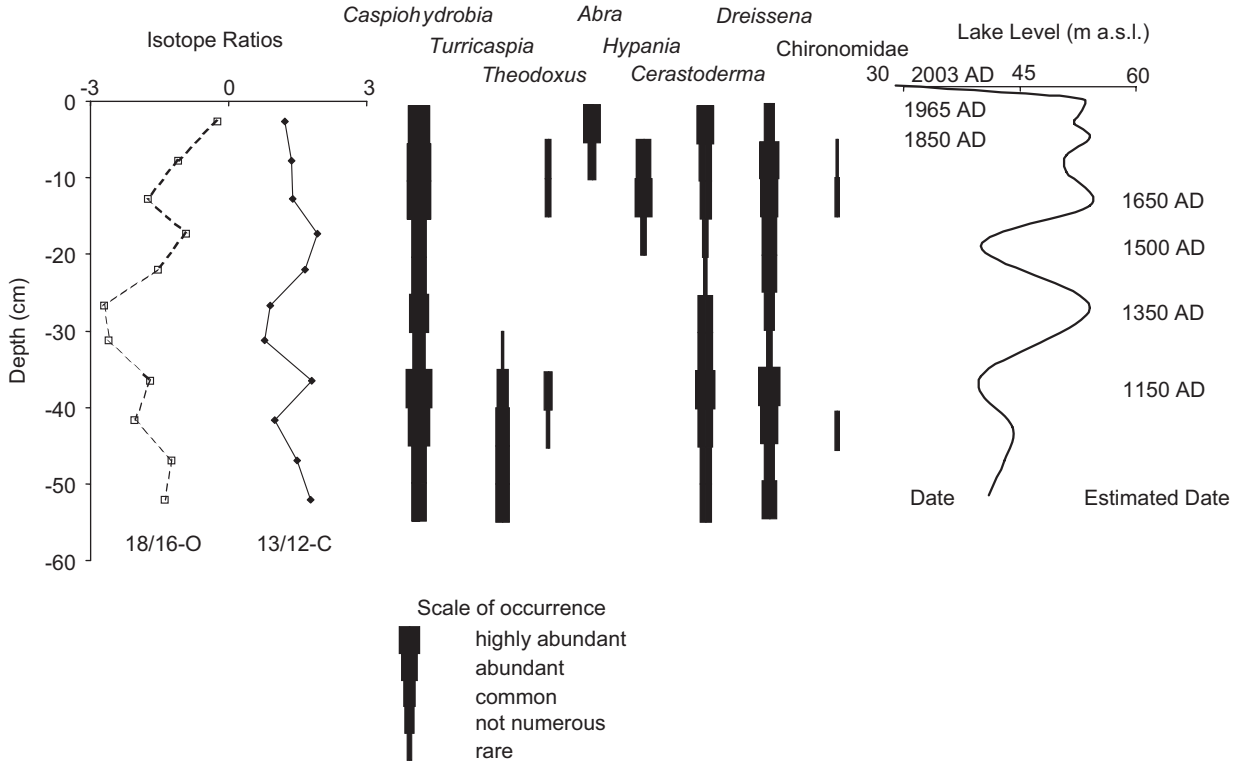


**Fig. 9.** Summarising diagram with sediment depth on the *y*-axis. Isotope curves show mean values of cores 136 and 139. Dynamics of molluscan occurrence composite of cores 136 and 139. Lake level curve with three documented and four estimated dates.

causes of environmental changes has to be studied in more detail if the modern catastrophic development of the Aral Sea is to be mitigated. It is emphasised that the understanding of natural hydrological dynamics needs palaeolimnological investigations in the catchment areas of the Amu Darya and the Syr Darya, using sediments of lakes which are not significantly affected by man.

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